

Nuclear Structure Theory and Experiment



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The structure of superheavy nuclei

P.H. Heenen¹

¹U.L.B. Bruxelles, Belgium

phheenen@ulb.ac.be

Super-heavy nuclei represent a tough challenge for nuclear theoreticians. These nuclei are indeed far from stability and from the region where the ingredients of nuclear models have been adjusted. Their existence is related to shell effects, whose prediction is thus crucial for the understanding of their structure. But due to the large number of nucleons, the level density is particularly high and the shell effects are more sensitive to the parameters of the model used to describe super-heavy nuclei than in any other regions of the mass table.

It is therefore particularly important to apply to the study of super-heavy nuclei models with the largest possible generality. In the last decade, several microscopic mean-field models have been applied to this region of the mass table. They share the property that their only phenomenological ingredient is an effective interaction which has been adjusted on very general properties of nuclei. Three main families of models have been used: Hartree-Fock-Bogoliubov methods with either a Skyrme interaction [1] or the Gogny force [2] and relativistic Hartree Bogoliubov (usually called relativistic mean-field) methods with an effective Lagrangian [3].

I shall review these methods and their particularities. I shall first focus on how they have been tested on nuclei close to the super-heavy region. The recent experimental results for the Nobelium isotopes ²⁵²No and ²⁵⁴No [4,5] are in this respect of particular importance. They bring data in a region close to the domain of super-heavy nuclei, where our knowledge of single-particle spectra and of pairing correlations is particularly limited. All three families of mean-field methods have been applied to these nuclei [5-7] and I shall compare their results.

I shall finally present some recent applications. I will stress the importance of a correct treatment of pairing correlations; I will also focus on the different ways odd nuclei are described and on the influence of the polarization effects due to the unpaired nucleon.

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Structure of nuclei in the mass 250 region

I. Ahmad¹

¹Argonne National Laboratory, USA

ahmad@phy.anl.gov

The nuclear structure of superheavy elements plays a very important role in the understanding and prediction of their nuclear properties. However, only few atoms of these nuclides can be produced because of the extremely low production cross sections. Thus, their structure must be deduced from systematics, using the information obtained on the structure of lower-mass nuclei. It is therefore essential to fully characterize the single-particle orbitals in nuclei that are available in sufficient quantities for such studies. The largest amount of the heaviest isotopes can be produced in the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory. This year we obtained extremely pure samples of ²⁵⁵Fm, ²⁵³Es and ²⁵¹Cf and studied their decay properties.

Extensive measurements of α -particle, conversion electron and γ -ray spectra have been performed with high-resolution semiconductor detectors. Alpha-particle spectra were measured by 25 mm² Passivated, Implanted, Planar Silicon (PIPS) detectors with resolutions (FWHM) of 9.2 keV. The α -particle energies directly provided the level energies in the daughter ²⁴⁷Cm. More precise level energies were determined from the γ -ray spectra measured with a Low Energy Photon Spectrometer (LEPS). Conversion electron spectra measured with a 6-mm x 6-mm PIN diode of 0.3 mm thickness provided the transition multipolarities. Half-lives of the 227.4- and 404.9-keV levels were measured by the alpha-gamma delayed coincidence technique. Gamma-ray spectra were also measured in prompt and delayed coincidence with α particles. From the results of these measurements, the level scheme shown in Fig. 1, has been constructed [1] and spins, parities and Nilsson state assignments have been deduced. We have established the following single-particle states: 9/2⁺[734], 0 keV; 5/2⁺[622], 227.4 keV; 7/2⁺[624], 285.1 keV; 1/2⁺[620], 404.9 keV; 1/2⁺[631], 518 keV. The experimental E2 transition rate between the 1/2⁺[620] and 5/2⁺[622] state was found to be ~ 100 times faster than the rate calculated with single-particle wavefunctions [2] and pair occupation probabilities [3]. The E2 matrix element is extremely sensitive to the pairing term because the 1/2⁺[620] orbital is a particle state and the 5/2⁺[622] orbital is a hole state. Thus the observed discrepancy could be either due to the incorrect pairing term and/or due to the admixture of the 1/2⁺[620] wavefunction in the 5/2⁺[622] state. Also, the E3 transition rate was measured between the 5/2⁺[622] and 9/2⁺[734] levels to be 5 Weisskopf units (W.u). This clearly demonstrates octupole mixing in the 5/2⁺[622] level. Similar octupole mixing was observed in the 5/2⁺[622] level in the isotope ²⁴⁹Cf [4].

The decay of ²⁵⁵Fm ($t_{1/2}=20.1$ h) was studied in 1998 and 2000 to investigate the level structure of ²⁵¹Cf, and the results from the 1998 study, which included gamma-gamma coincidence measurements with Gammasphere, were published [5] in 2000. In that study we were able to establish the assignment of the 1/2⁺[750] Nilsson orbital to the 632-keV level. In addition, a $K^\pi=3/2^-$ and a 7/2⁺ bands were identified at 982 and 1078 keV, respectively. The former was interpreted as the 2⁻ octupole band coupled to the 7/2⁺[613] orbital and the latter was interpreted as the β band coupled to the 7/2⁺[613] configuration. We have measured the γ -singles spectra with a new source this year, which had less Es and other contaminants than previous samples. Also, gamma-gamma coincidence measurements were performed with Gammasphere. The results of these measurements confirm our earlier published results.

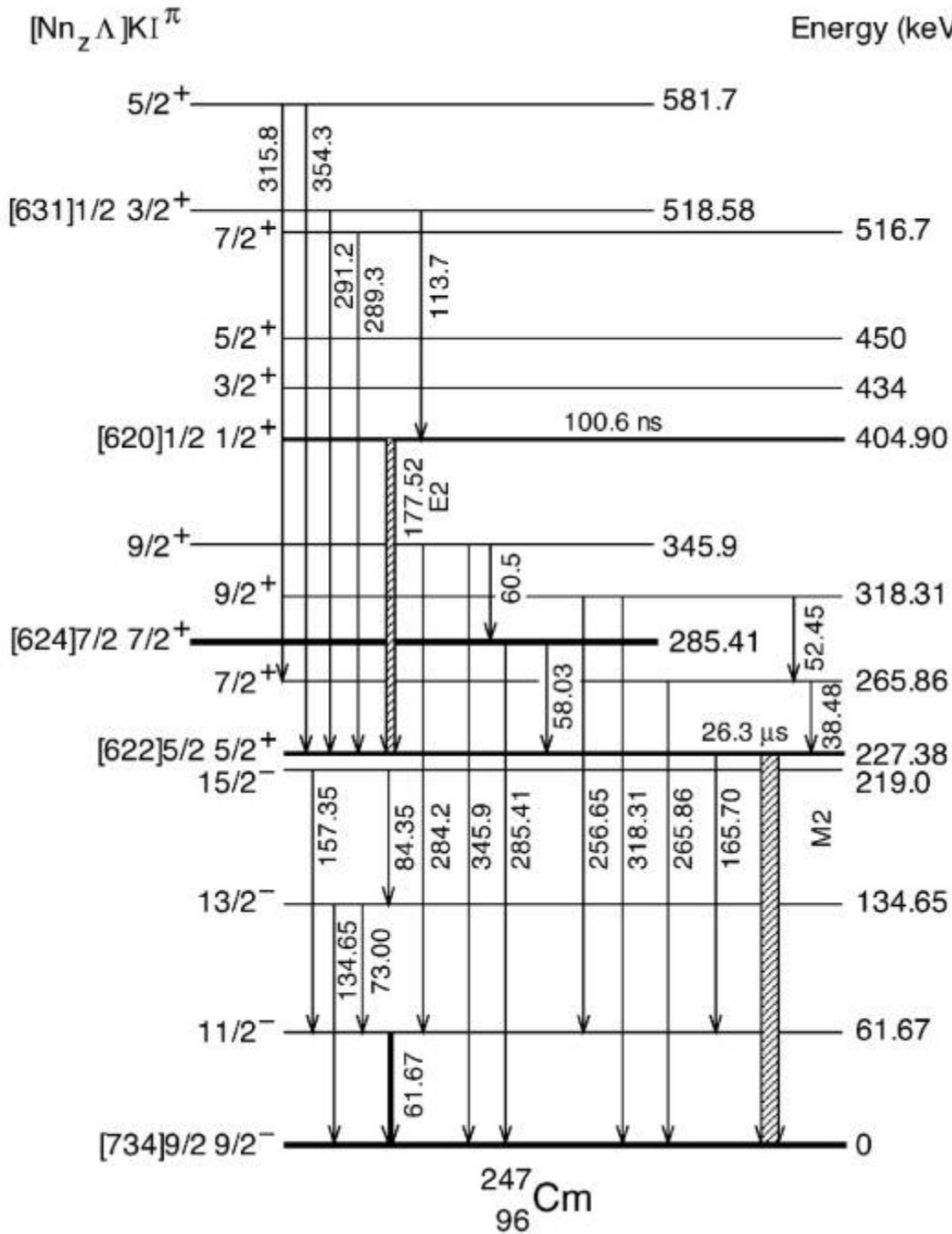


Figure 1. Level scheme of ^{247}Cm deduced from the study of ^{251}Cf alpha decay.

To investigate proton levels in ^{249}Bk we have used 1 mg ^{253}Es ($t_{1/2}=20.47$ d) for γ -singles and gamma-gamma coincidence measurements. This sample had an order of magnitude less ^{254}Es than any previous sample. This has allowed us to detect low-intensity γ rays. By following the decay of the γ -ray lines we have been able to assign gamma rays to ^{253}Es decay. Gamma-gamma coincidence measurements were performed with Gammasphere using 1 mg source. Data were accumulated for 5 days and are being

analyzed. By combining the results of the present investigation with (α ,t) and (^3He ,d) reaction spectroscopy data [6], we hope to make a definite identification of the $1/2^-$ [521], $7/2^-$ [514] and $9/2^+$ [624] Nilsson orbitals in ^{249}Bk .

Calculations of single-particle spectra were made using a Woods-Saxon potential and pairing interaction [3] and these are in fair agreement with the observed level energies.

Acknowledgements

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Nuclear structure investigations of heavy actinide and trans-actinide isotopes

F.P. Hessberger¹

¹Gesellschaft für Schwerionenforschung, Germany

F.P.Hessberger@gsi.de

Introduction

Approximately 35 years ago the search for superheavy elements (SHE) was initiated by extrapolations of the nuclear shell model into regions far above the heaviest nuclei ($Z=103$) known at that time. The next (spherical) closed proton and neutron shells above the doubly magic nucleus ^{208}Pb were predicted at $Z=114$ and $N=184$ [1]. A large number of new nuclides having $Z > 100$ was identified since then, but for most of them only some basic decay properties could be measured due to low production rates. Significant enhancement of the experimental sensitivity during the past years now allows detailed decay studies for numerous isotopes up to $Z=108$. Those results deliver valuable information on the nuclear structure of these nuclei or their decay products, thus forming a framework for further developments of enhanced theoretical predictions of properties of still unknown superheavy nuclides.

Experimental Procedure

Information on the structure of transfermium nuclei can be obtained so far as well by decay spectroscopy as by in-beam spectroscopy. In the latter case detectors suited to measure radiation (γ -rays, conversion electrons(CE)) emitted during the deexcitation process of the compound nucleus are placed close to the target position. It delivers information on nuclear levels populated during the deexcitation process after particle emission, i.e. information on the structure of the evaporation residue (ER). In-beam spectroscopy of transfermium nuclei so far has been performed at the RITU separator, Jyväskylä (Finland) and the AMS, Argonne (USA) to investigate isotopes of nobelium [2,3,4] and fermium [3].

Most of the information on the nuclear structure of transfermium isotopes, however, has been obtained by means of decay spectroscopy. In most of the set-ups used presently [5,6] the isotopes of interest are separated in-flight from the projectile beam and are implanted into an arrangement of Si-detectors ('stop detector'), used to measure the α -decay energies. γ -rays emitted in coincidence to α -particles are measured with Ge-detectors mounted directly behind the Si-detectors, while CE may be measured in a 'box' of Si-detectors surrounding the 'stop detector'.

We will report here (part of) the results from recent nuclear structure investigations performed at SHIP (GSI Darmstadt). The isotopes $^{254,253}\text{Lr}$, $^{251-253}\text{No}$, $^{246,247}\text{Md}$ have been produced in bombardments of $^{206,207}\text{Pb}$, ^{209}Bi with ^{48}Ca or ^{209}Bi with ^{40}Ar projectiles. Their radioactive decays as well as those of their daughter products have been investigated by means of α - and α - γ -coincidence spectroscopy. Data analysis is still in progress, so the results have to be regarded as preliminary.

Experimental Results

Low Spin Isomeric States in Odd Mass Nuclei

Detailed investigation of the decay properties of transfermium nuclei in the vicinity of $N=152$ during the past years has shown that the occurrence of isomeric states decaying by α -emission with half-lives typically in the order of (0.1-10) s is a widespread phenomenon. According to Weisskopf estimations a spin difference of at least $\Delta I=3$ between the isomeric state and subjacent levels is necessary in order that α -emission can compete with internal transitions in the range of those half-lives. In principle, two combinations, low spin ground state - high spin isomeric state or high spin ground state - low spin isomeric state are possible. An example for the first possibility is ^{257}Rf , where an $11/2^- [725]$ - isomeric state at $E^*=118$ keV above the $1/2^+ [620]$ - ground state was identified [7]. More frequent, however, appear low spin isomeric states above high spin ground states. Isomeric states in ^{257}Db and ^{253}Lr [6] as well as a spontaneous fission activity of $T_{1/2}=0.23$ s observed in the reaction $^{40}\text{Ar} + ^{209}\text{Bi}$ and attributed to $^{247\text{m}}\text{Md}$ [8] had been interpreted in this way. In our recent irradiation of ^{209}Bi with ^{40}Ar an α -emitter of $E_\alpha=8785$ keV with a half-life of $T_{1/2}=(0.26 \pm 0.6)$ s was observed, representing the α -decay branch of $^{247\text{m}}\text{Md}$. In back dated measurements α -decay from isomeric states, e.g. ^{257}Rf , ^{257}Db , ^{253}Lr , often was not recognized due half-lives similar to that of the ground state decay. Higher production rates, allowing more precise half-life measurements and resulting in higher numbers of α - α correlations, thus giving observation or non-observation of (correlated) α -lines a higher statistical significance, have solved this problem in several cases (see above). In our recent experiments we confirmed α - decay from an isomeric state in ^{255}Lr [9] and identified an isomeric state in ^{251}No ($T_{1/2}=0.93$ s). The corresponding α -line of $E_\alpha=8665$ keV had been already reported by Ghiorso et al.[10], but was never observed within the α -decay chain of ^{255}Rf [6,7]. A direct production by $^{206}\text{Pb}(^{48}\text{Ca},3n)^{251}\text{No}$ clearly showed in addition to the $E_\alpha=8610$ keV - transition an α -line of 8665 keV, correlated to an α -decay of $E_\alpha=8170$ keV, $T_{1/2}=4.3$ s (see fig. 1). The latter activity had already been observed in irradiations of ^{239}Pu with ^{12}C and was attributed to the decay of an isomeric state in ^{247}Fm [11].

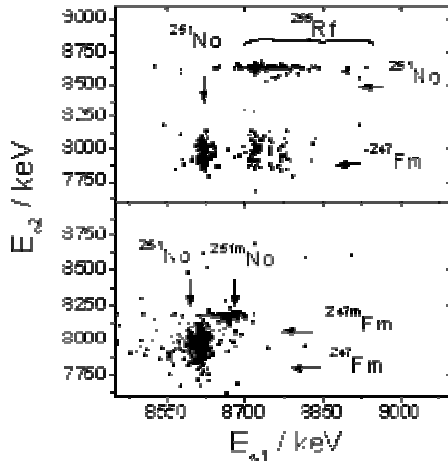


Figure 1. α - α correlation plot for a) evaporation residues produced in the reaction $^{50}\text{Ti} + ^{207}\text{Pb}$ at $E = (4.77-4.86)$ AMeV, b) $^{48}\text{Ca} + ^{206}\text{Pb}$ at $E = 4.81$ AMeV.

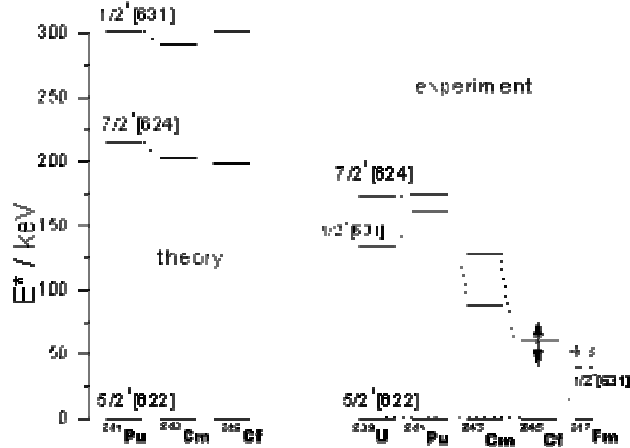


Figure 2. Comparison of calculated [14] and experimental Nilsson levels of $N=147$ isotones.

Nilsson Levels in Odd Mass Even Z Nuclei

In even Z – isotopes similarities in α -decay properties and nuclear structure are known for isotonic odd mass nuclei. These correlations have been used to explain the α -spectra of $^{257,255}\text{Rf}$, ^{253}No [6,7,12,13] and to construct partial level schemes for the daughter nuclei. The recent experiments at SHIP delivered enhanced decay data for ^{249}Fm , ^{251}No and thus allowed to extend such comparisons to the N=149 – isotones and their N=147 – decay products. Level predictions of Cwiok et al. [14] for the N=147 – isotones are compared with experimental results in Fig. 2. Cwiok et al. predict the $5/2^+[622]$ – Nilsson level as the ground-state of these nuclei, which is in line with the (older) experimental assignments, and rather stable excitation energies for the $7/2^+[624]$ – level, which is assigned to the ground-state of the N=149 – mother nuclei, and the $1/2^+[631]$ –level. Experimental assignments, however, place the $1/2^+[631]$ below the $7/2^+[624]$ – level and exhibit for both levels a drastic decrease of the energies from ^{241}Pu to ^{243}Cm [15].

In our experiments ^{249}Fm was produced by $^{207}\text{Pb}(^{48}\text{Ca},2n)^{253}\text{No} - \alpha \rightarrow ^{249}\text{Fm}$. Its α -line was significantly broader than that of ^{250}Fm , which was produced in the same irradiation by α -decay of ^{254}No . No γ -rays were observed in coincidence with α -decays of ^{249}Fm . Using the line width of ^{250}Fm , the ^{249}Fm , the α -spectrum was disentangled into two components of $E_\alpha=(7559\pm10)$ keV and $E_\alpha=(7583\pm10)$ keV. This line form was interpreted as due to energy summing of α -particles with conversion electrons either being stopped in the detector or leaving it. Taking into account that difference, maximum and minimum energy shifts of α -particles of $\Delta E_{\text{max}}=E^*-8$ keV and $\Delta E_{\text{min}}=21$ keV, as obtained from α - γ -coincidence measurements of ^{253}No , we obtain an excitation energy of the level populated by the α -decay of $E^*=(53\pm10)$ keV. Non-observation of γ -rays in coincidence with α -particles indicates that this value is already an upper limit. Respecting the number of observed α -decays and the efficiency of the Clover detector we obtain a lower limit for the conversion coefficient $\alpha_L > 50$, which refers to γ – energies $E_\gamma < 50$ keV for an M1 – transition [16].

For ^{251}No we observed a single narrow α -line of $E_\alpha=(8110 \pm 10)$ keV (FWHM=21 keV). No γ – events in coincidence with α -particles were observed. Thus it is seemingly not influenced by energy summing K- or L- conversion electrons, which indicates that the $7/2^+[624]$ – level in ^{247}Fm is already located below the L-electron binding energy ($E^* < 20$ keV). The observation of an isomeric state $^{247\text{m}}\text{Fm}$ ($1/2^+[631]$) decaying by α -emission with a half-life of 3 s, however, suggests that the $7/2^+[624]$ – level already forms the ground state since a γ - decay life-time > 1 s is rather expected for a $\Delta I=3$ – transition (M3), than for a $\Delta I=2$ – transition (E2) expected for $1/2^+[631] \rightarrow 5/2^+[622]$.

Nilsson Levels in Odd Mass Odd Z Nuclei

In odd Z nuclei similarities in α -decay properties and nuclear structure are known for isotopic odd mass nuclei. These correlations can be used to explain the α -spectra and to construct partial level schemes for the daughter nuclei. On the other hand, changes in the decay pattern may reveal a change of the ground state configuration of the daughter nuclei. Our investigations so far concentrated on the nuclei in the range $Z=(99-105)$ characterised by $T_z=45, 47, 49$. Partial level schemes for these nuclides as derived on the basis of recent experiments at SHIP and literature data are shown in fig. 3.

The decay scheme of ^{257}Db has been discussed in detail in ref. [6]. Ground state was assigned as $9/2^+[624]$ as predicted by Cwiok [14], isomeric state as $1/2^+[521]$. Isomeric decay populates an isomeric state in ^{253}Lr , decaying into $1/2^-$ – state in ^{249}Md . Whether this state decays by α -emission is presently still unclear.

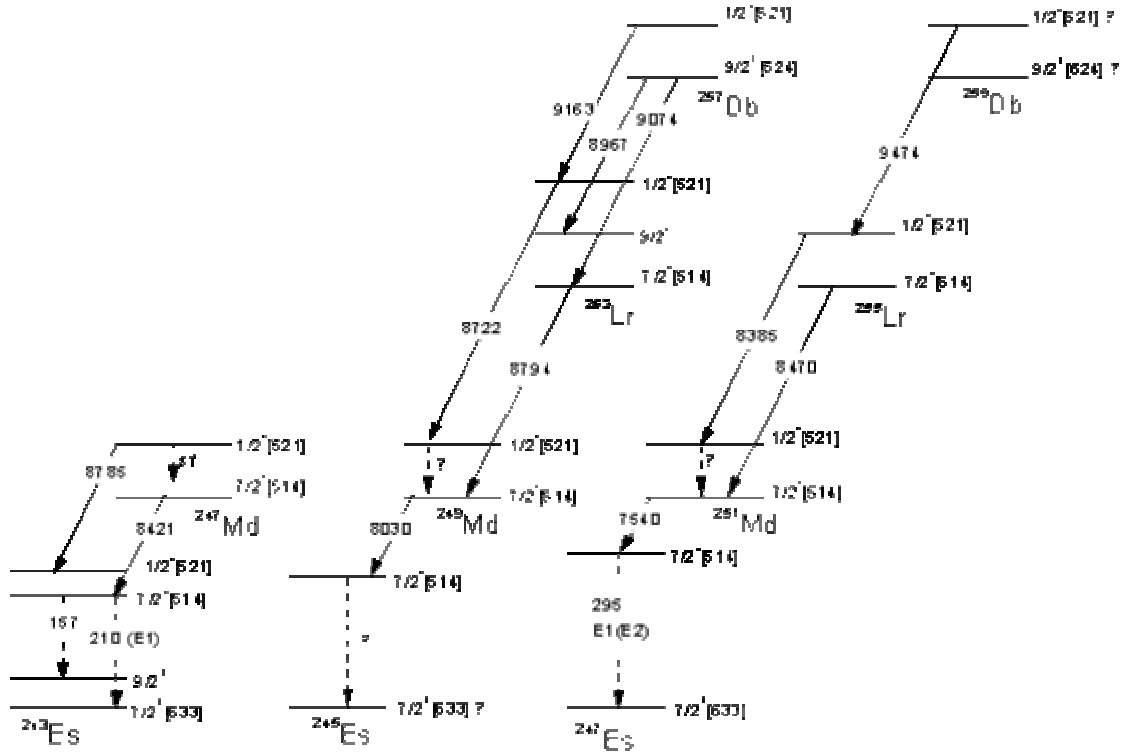


Figure 3. Adopted decay schemes for $T_z=45, 47, 49$ – odd Z isotopes. Level schemes and decay data are partly tentative and preliminary.

No statistically significant difference in α -decays of ^{249}Md following either $^{253\text{m}}\text{Lr}$ or ^{253}Lr have been observed so far. It was argued, however, that the decay pattern of $^{257\text{m}}\text{Db}$ and ^{257}Db exclude the $1/2$ -[521] Nilsson level as ground-state of ^{249}Md as predicted [14], but favour the $7/2$ -[514] level.

Similarities for the neighbouring $T_z=49$ – isotopes are evident. The two α -lines of ^{255}Lr are found to have different half-lives and thus represent the decay from different levels: $^{255\text{m}}\text{Lr}$ ($E_\alpha=8470$ keV, $T_{1/2}=2.1$ s), ^{255}Lr ($E_\alpha=8375$ keV, $T_{1/2}=16.4$ s). In analogy to the case of $^{253,253\text{m}}\text{Lr}$ the α -line of the higher energy has been attributed to the decay of the isomeric state. For the mother nucleus, ^{259}Db , only one α -lines has been reported so far [17]. The α - α -correlations observed by Gan et al. [17] suggest an assignment to an isomeric state similar to ^{257}Db . No statistically significant differences in the α -energy of ^{251}Md events following α -decays of either ^{255}Lr or $^{255\text{m}}\text{Lr}$ are observed. Also no γ -decays in coincidence with each of these lines were registered, while in coincidence with α -decays of ^{251}Md a 295.1 keV γ -line as well as some Es-x-ray – events were observed. The ratio $\Sigma\text{x-rays} / \Sigma\gamma$ suggest an E1-transition, which corroborates the ground-state level assignment $7/2$ -[514] and $7/2$ -[633] for ^{251}Md and ^{247}Es , respectively.

For the $T_z=45$ – members only α -decay of ^{247}Md and ^{243}Es was measured so far. The α -line at E_α 8421 keV was found in coincidence with a γ -line of 210 keV [12]. On the basis of coincidences with K-x-rays and an energy shift of the α -line due to energy summing with conversion electrons it was concluded that the γ -line represents rather an E1 – transition, which excludes a level assignment $3/2$ -[521] for the ground-state of ^{243}Es [18], but an E2 – transition, which would favour the latter assignment could not be excluded [12]. A repetition of this measurement clearly proved the E1 – character, suggesting $7/2$ -[633] as the

ground-state level of ^{243}Es . In addition an α - γ – coincidence $E_\alpha=8471\text{ keV} - E_\gamma=157\text{ keV}$ was observed. It is tentatively assigned to γ -decay from the $7/2-[514]$ – level into the first excited member of the ground state rotational band ($9/2^+$) of ^{243}Es .

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Spectroscopy of the heaviest elements

R. Julin¹

¹JYFL University of Jyväskylä, Finland

rauno.julin@phys.jyu.fi

The anomalously high production cross-section of about 2 microbarn for the cold fusion reaction $^{208}\text{Pb}(^{48}\text{Ca},2n)^{254}\text{No}$ was utilized in the in-beam gamma-ray studies of ^{254}No , where the Gammasphere array was combined with the Fragment-Mass-Analyzer (FMA) at Argonne [1] and the Ge clover array (SARI) was combined with the RITU-gas-filled-separator at JYFL in Jyväskylä [2]. By employing the recoil-gating and recoil-decay-tagging (RDT) techniques the yrast line of ^{254}No was identified revealing that the ^{254}No nucleus is deformed with a deformation parameter, $b_2=0.27(2)$.

For further studies of ^{254}No , the SACRED magnetic solenoid electron spectrometer was combined with RITU for in-beam electron RDT measurements. In a careful analysis of resulting prompt recoil-gated electron-electron coincidence spectra of ^{254}No it was found that a broad distribution under the discrete electron lines arising from transitions within the ground state band in ^{254}No is not due to random events but consists of high-multiplicity events, obviously originating from cascades of highly converted M1 transitions within rotational bands built on high K states in ^{254}No [3].

Following the success of the RDT experiments at JYFL, the Jurosphere2 array + RITU system was employed in an in-beam gamma-ray study of ^{252}No for which the production cross-section in the $^{206}\text{Pb}(^{48}\text{Ca},2n)$ reaction is only 300 nanobarn [4]. The yrast rotational band of ^{252}No was observed up to $I=20$ indicating that ^{252}No is less deformed than ^{254}No and showing evidence for quasiparticle alignment. Both the ^{254}No and ^{252}No data reveal that the fission barrier exists at least up to $I \sim 20$ in these nuclei.

In order to gain experimental knowledge of single-particle states in heavy nuclei the next in-beam recoil-tagging experiment in Jyväskylä was focused on ^{255}Lr and in Argonne on ^{253}No . They were produced via the $^{209}\text{Bi}(^{48}\text{Ca},2n)$ and $^{207}\text{Pb}(^{48}\text{Ca},2n)$ reactions, with cross-sections of about 300 nanobarn and 500 nanobarn, respectively. Strong X-ray peaks in the resulting spectra indicate that the decay along the yrast line of these nuclei proceeds by strongly converting M1 transitions, which calls for electron-spectroscopic methods.

In the present contribution, the results obtained at Jyväskylä will be discussed in more detail. New data from the on-going RDT campaign at JYFL with the new JuroGam array and the GREAT spectrometer combined with RITU will be shown.

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Properties of superheavy nuclei

R. Smolanczuk¹

¹Soltan Institute for Nuclear Studies, Poland

smolan@fuw.edu.pl

Alpha-decay and spontaneous-fission of deformed and spherical superheavy nuclei are discussed. Calculations are performed in the framework of a macroscopic-microscopic model. Spontaneous fission is described in a dynamical approach. Half-lives of heaviest nuclear systems are compared with experimental data. Some conclusions and remarks on the possibility of forming and detecting still heavier elements are presented.

Structure of superheavy elements with meson field theory

W. Greiner¹

¹Institut für Theoretische Physik, Universität Frankfurt, Germany

greiner@th.physik.uni-frankfurt.de

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Limits of stability, formation mechanism and structure of shell-stabilized heavy nuclei

T.L. Khoo¹, P. Reiter², A. Afanasjev¹, I. Ahmad¹, A. Heinz¹, T. Lauritsen¹, C.J. Lister¹, D. Seweryniak¹, N. Amzal³, P.A. Butler³, M.P. Carpenter¹, A.J. Chewter³, J.A. Cizewski⁴, C.N. Davids¹, S. Frauendorf⁵, P.T. Greenlees⁶, K. Helariutta⁶, R.D. Herzberg³, G. Jones³, R.V.F. Janssens¹, R. Julin⁶, H. Kankaanpää⁶, H. Kettunen⁶, F. Kondev¹, P. Kuusiniemi⁴, G.A. Lalazissis⁷, M. Leino⁶, A.A. Sonzogni¹, S. Siem¹, I. Wiedenhöver¹, J. Uusitalo⁶

¹ Argonne National Laboratory, USA

² University of Munich, Germany

³ University of Liverpool, United Kingdom

⁴ Rutgers University, USA

⁵ University of Notre Dame, USA

⁶ University of Jyväskylä, Finland

⁷ Aristotle University of Thessaloniki, Greece

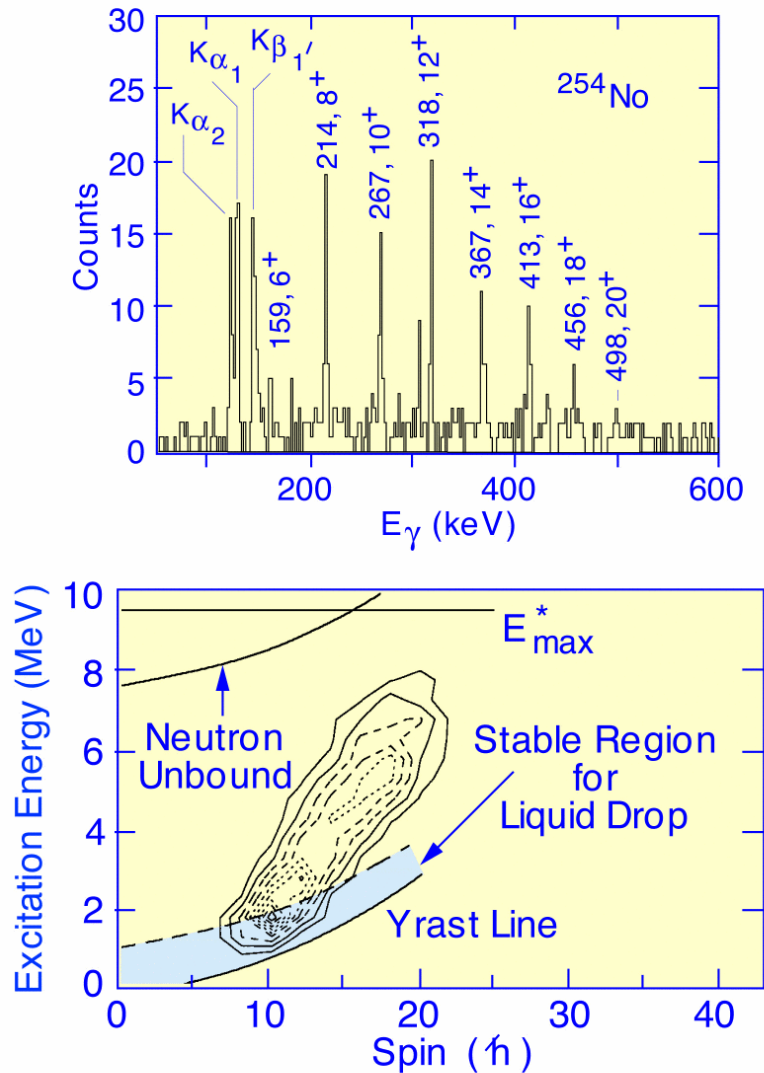
khoo@anl.gov

Recent experiments and theoretical calculations have shed new light on heavy nuclei that are stabilized by the shell-correction energy. This abstract describes results from experiments with Gammasphere and the Fragment Mass Analyzer at Argonne [1-2], and compares these results with those from recent self-consistent mean-field models. The experimental data provide information on: (i) the limits of stability as functions of spin and excitation energy; (ii) the fission barrier as a function of spin; (iii) the survival probability against fission of hot nobelium nuclei [from (i and ii)], which is critical for understanding the formation mechanism of superheavy nuclei; (iv) the importance of high partial waves in the synthesis of superheavy nuclei; (v) the moments of inertia of rotational bands in ^{253,254}No; and (vi) a neutron quasiparticle energy from ²⁵³No. As an example, the first figure below shows a spectrum of the ground-state band of ²⁵⁴No up to spin 20 and the entry distribution (in spin and excitation energy), which reveals that ²⁵⁴No survives fission up to at least 22 hbar in spin and 8 MeV excitation energy and that the fission barrier above spin 10 hbar is at least 5 MeV. Clearly the entry distribution extends well beyond the blue shaded region, which denotes the stability limits of a rotating liquid drop, thereby graphically illustrating the additional stability given by the shell-correction energy. Experiments at Jyväskylä, with RITU in combination with various Ge arrays and an electron spectrometer, have also revealed the properties of ²⁵²No [3], as well as of ²⁵⁴No.

Calculations have been performed in the framework of non-relativistic and relativistic self-consistent mean field theories (see, for example, [4-7]), as well as with the microscopic-macroscopic approach (by Sobiczewski *et al.*). For the self-consistent mean-field models, the heaviest nuclei provide an especially interesting test since the effective forces have been selected from fits to the bulk properties of "normal" lighter nuclei, where the binding comes predominantly from the liquid-drop term (from the viewpoint of the Strutinsky approach). In brief, the self-consistent models (i) provide good descriptions of the moments of inertia of ^{252,253,254}No, although details of the variation with A and spin are not fully described; (ii) suggest that the fission barrier remains large at high spin [4-5], in agreement with experimental entry distribution measurements; and (iii) reproduce many quasiparticle energies of deformed nuclei within 0.5 MeV, although there are systematic discrepancies of >1 MeV for certain classes of orbitals--results [6] with the NL1 and NL3 Lagrangians are given in the second figure below. Ref. [6] presented the first systematic test of the accuracy of self-consistent mean-field quasiparticle energies, by examining the known quasiparticle states in the transuranic nuclei ²⁴⁹Bk and ^{249,251}Cf. (A similar test has been conducted in [7]). The third figure compares experimental and theoretical kinematic and dynamic moments of

inertia, $J^{(1)}$ and $J^{(2)}$, for $^{252,254}\text{No}$ and for the $7/2^+[624]$ band in ^{253}No . The upper panel shows the results from experiment [1-3] and the lower panel presents results from the Skyrme Hartree-Fock Bogolubov model [7]. The magnitudes and general trends are reproduced by theory, but details, such as the variation with spin and mass, are not in perfect agreement, probably due to some imperfections in the energies of high- j single-particle orbitals.

Limits of Stability in Spin and Energy



^{254}No is stable up to at least spin $22\hbar$ and 8 MeV energy -- much more robust than expected.

$$B_f(\ell) > 5 \text{ MeV} \quad \ell \geq 10 \hbar$$

Gammasphere at ANL

Reiter et al.

PRL 84, 3542 (2000)

Figure 1.

Acknowledgements

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Charge and mass renormalization in no-photon QED

H. Siedentop¹, C. Hainzl¹

¹Ludwig-Maximilians-Universitaet Muenchen, Germany

h.s@lmu.de

Starting from a formal Hamiltonian as found in the physics literature - omitting photons - we define a renormalized Hamiltonian through charge and mass renormalization. We show that the restriction to the one-electron subspace is well-defined. Our construction is non-perturbative and does not use a cut-off.

The Hamiltonian is relevant for the description of the Lamb shift in muonic atoms.

Conversion electron measurement for the α decay of ^{257}No

M. Asai¹, K. Tsukada¹, S. Ichikawa¹, Y. Nagame¹, T. Ishii¹, I. Nishinaka¹, K. Akiyama¹, A. Osa¹, M. Sakama², Y. Oura³, K. Sueki⁴, M. Shibata⁵

¹ Japan Atomic Energy Research Institute, Japan

² University of Tokushima, Japan

³ Tokyo Metropolitan University, Japan

⁴ University of Tsukuba, Japan

⁵ Nagoya University, Japan

asai@tandem.tokai.jaeri.go.jp

The stability of superheavy nuclei is one of the most interesting subjects in nuclear physics. This stabilization is caused by nuclear shell effects. Many theoretical studies have predicted the shell structure around the superheavy region, while the experimental information is very scarce. In particular, little is known about the level structure, e.g. level energies of excited states, spin-parities and single-particle configurations of the ground state as well as the excited states, and γ transitions between them. The aim of this study is to establish Nilsson single-particle states in odd-mass $Z>100$ and $N>152$ nuclei through experimental spin-parity assignments for the ground state as well as excited states by means of α - γ and α -conversion electron spectroscopy. In this presentation, we report our first results on the α decay of ^{257}No .

The nucleus ^{257}No was produced by the $^{248}\text{Cm}(^{13}\text{C},4n)$ reaction at the JAERI tandem accelerator facility. Reaction products recoiling out of the targets were thermalized in He gas loaded with PbI_2 clusters, and transported into a surface ionization-type thermal ion source of the JAERI on-line isotope separator (ISOL) with a gas-jet transport system [1]. Mass-separated ions were implanted into a Si PIN photodiode detector (9 mm \times 9 mm \times 0.3 mm³) around which another three photodiodes were placed to detect α particles and electrons simultaneously. Energy calibration of the detectors was performed using a mass-separated ^{221}Fr source implanted into the same Si detector by this ISOL system before and after the on-line experiment, and also using an ^{241}Am source. Energy resolution of the detectors was 2.1 keV (FWHM) for 59 keV γ rays, and about 3.5 keV for 100 keV electrons. Typical γ and electron spectra of ^{241}Am and ^{221}Fr are shown in Fig. 1.

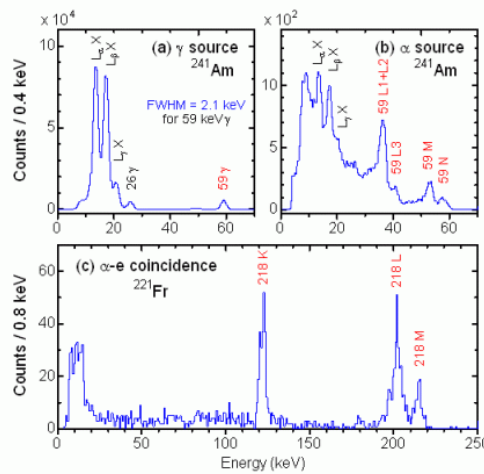


Figure 1. Typical γ and electron spectra measured by a Si PIN photodiode detector. (a) Gamma-ray spectrum for an ^{241}Am γ source. (b) Gamma and electron spectrum measured using an ^{241}Am α source. (c) Electron spectrum in coincidence with 6126 keV α particles of ^{221}Fr .

Figures 2(a) and (b) show an α singles spectrum for the mass-257 fraction and an electron spectrum in coincidence with the 7500-8500 keV α particles. As shown in Fig. 2(b), two prominent electron peaks are observed at 50.0 and 97.4 keV, which correspond to the L internal-conversion electrons of the 77.5 and 124.9 keV γ transitions in ^{253}Fm , respectively. The M electron peaks are also observed at 70.4 and 117.6 keV. Taking into account the α -e and e-e coincidence relationships, we have established a newly proposed decay scheme of ^{257}No given in Fig. 3 together with a previously evaluated one [2,3]. It has been revealed that the 8323 keV α transition populates the excited state of ^{253}Fm , not the ground state, and the 8270 keV transition does not exist in the decay scheme; this α peak arises from the coincidence summing effect between the 8222 keV α particles and the 50 keV electrons.

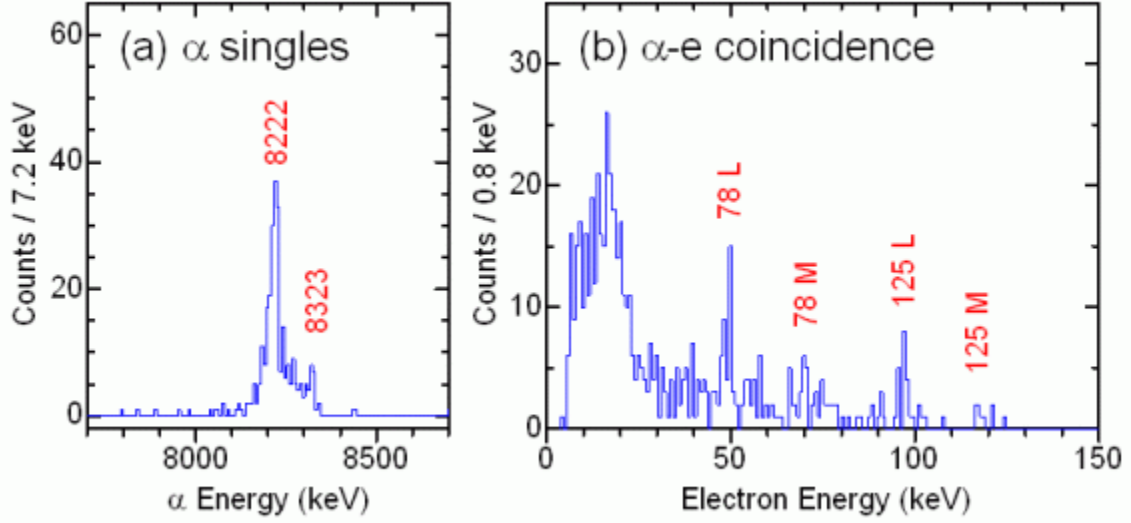


Figure 2. (a) Alpha singles spectrum for ^{257}No measured by a detector with a 20% detection efficiency. (b) Electron spectrum in coincidence with 7500-8500 keV α particles of ^{257}No .

Theoretical L internal conversion coefficients (ICCs) of a 125 keV γ transition in $Z=100$ nuclei (α_{L1} , α_{L2} , α_{L3}) are (0.031, 0.021, 0.015), (0.33, 4.3, 2.3), and (4.0, 0.48, 0.014) for E1, E2, and M1 multiplicities, respectively [4]. The observed electron/ α intensity ratio allows us to exclude the E1 assignment for both the 78 and 125 keV transitions owing to small ICCs of E1 transitions. The L3 ICC of E2 transitions is about a half of the L1+L2 ICC, while that of M1 transitions is negligibly small. The observed L electron spectra show no such a large L3 component. Therefore, the M1 multipolarity is assigned to both the 78 and 125 keV transitions. Since the spin-parity of the ground state of ^{253}Fm is $1/2^+$, that of the 125 keV level is either $1/2^+$ or $3/2^+$. The 125 keV level is populated by the allowed α transition with $\text{HF}=1.3$, indicating that the configuration of this level is the same as that of the ground state of ^{257}No . Only the $3/2[622]$ state could lie at such low energy in ^{253}Fm among the Nilsson single-particle states with a spin $1/2^+$ or $3/2^+$. Thus, we assign the $3/2[622]$ configuration to the ground state of ^{257}No as well as the 125 keV level in ^{253}Fm . The 24 and 47 keV levels would be the $3/2^+$ and $5/2^+$ members of the $1/2[620]$ band whose energies are consistent with those in neighboring nuclei.

In conclusion, excited states in ^{253}Fm populated via the α decay of ^{257}No have been established through α -e coincidence spectroscopy. Spin-parities of the ground state of ^{257}No as well as the excited states in ^{253}Fm were determined from the multipolarity of γ transitions and α decay hindrance factors. The $3/2[622]$ configuration was assigned to the ground state of ^{257}No , which is different from the ground state of other $N=155$ isotones ^{255}Fm and ^{253}Cf having the $7/2[613]$ configuration. Next experiment, we will measure α - γ coincidences for the α decay of ^{261}Rf to establish excited states in ^{257}No and assign spin-parities of the

ground state of ^{261}Rf as well as the excited states in ^{257}No based on the present spin-parity assignment for the ground state of ^{257}No .

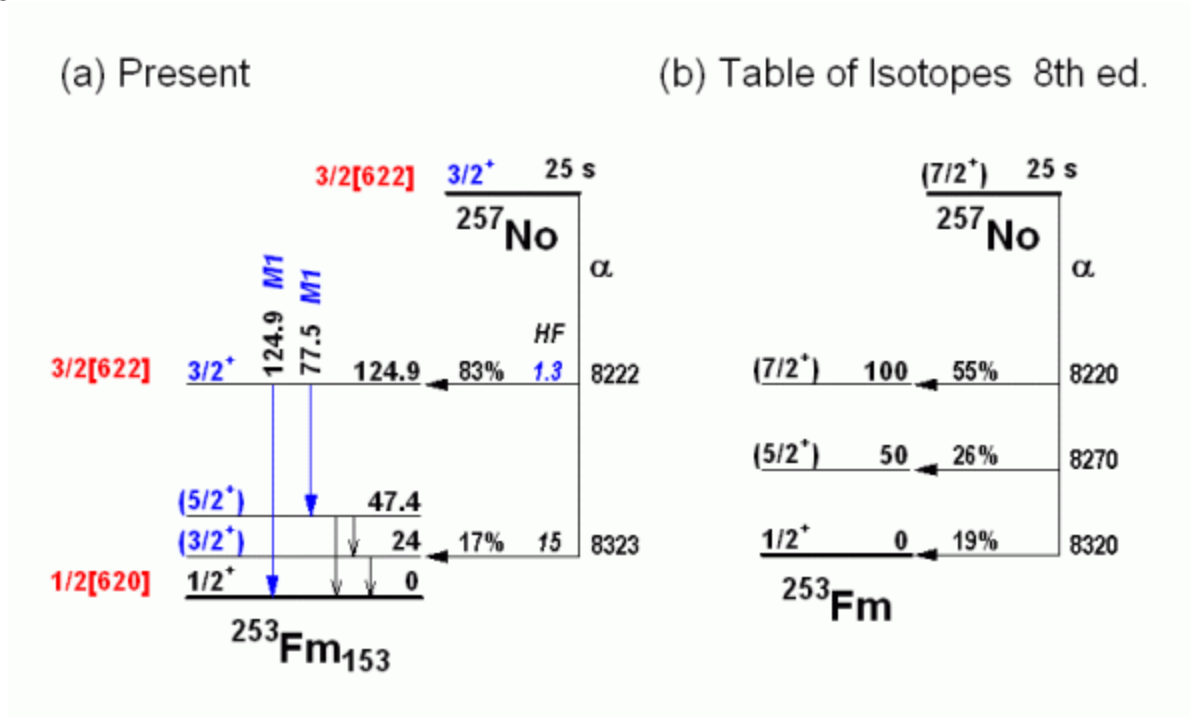


Figure 3. (a) A newly proposed decay scheme of ^{257}No established on the basis of the present experimental result. (b) A previously evaluated one in Refs. [2,3].

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Pairing correlations in superheavy nuclei

Z. Patyk¹

¹Soltan Institute for Nuclear Studies, Poland

zygmunt.patyk@fuw.edu.pl

In theoretical description of atomic nucleus very important role plays pairing correlations. Direct mass measurements of nuclei carried out at GSI-Darmstadt [1] opens a new possibility to predict the pairing force at the region of heavy and superheavy nuclei. We have tested, in the macroscopic-microscopic approach [2], a sensitivity of the theoretical description of properties of superheavy nuclei as a function of the strength of pairing forces. Basic properties for superheavy nuclei as odd-even nuclear mass staggering, a height of fission barrier, Q_α and a neutron separation energy are discussed. Recently superheavy nuclei are intensively investigated in many laboratories [eg. 3,4].

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Investigation of the decay property of extremely low-lying isomer $^{229\text{m}}\text{Th}$

Y. Kasamatsu¹, H. Kikunaga², K. Takamiya³, T. Mitsugashira⁴, T. Nakanishi², T. Ohtsuki⁴, H. Yuki⁴, W. Sato¹, H. Yamana³, Y. Ohkubo³, H. Kimura¹, S. Shibata³, Y. Kawase³, A. Shinohara¹

¹ Osaka University, Japan

² Kanazawa University, Japan

³ Kyoto University, Japan

⁴ Tohoku University, Japan

kasamatu@chem.sci.osaka-u.ac.jp

Introduction

The chemical and physical properties of the isomeric state of ^{229}Th , having the lowest excitation energy, is an interesting subject in both experiment and theory. Helmer and Reich reported that the excitation energy of $^{229\text{m}}\text{Th}$ is about 3.5 eV from the result of precise γ -ray spectroscopy for the α -decay of ^{233}U [1]. A simplified level scheme of ^{229}Th is shown in Fig.1. This level corresponds to a $3/2^+$ [631] Nilsson state while the ground state to a $5/2^+$ [633] one [2]. The emission of internal conversion electrons is forbidden because the excitation energy is lower than the first ionization energy of thorium atoms. Thus the deexcitation from $^{229\text{m}}\text{Th}$ to the ground state is expected to occur through a direct γ -ray transition. Furthermore, if the outer-shell electron of $^{229\text{m}}\text{Th}$ can be involved in the decay of $^{229\text{m}}\text{Th}$ nucleus, $^{229\text{m}}\text{Th}$ may decay via an electron bridge (EB) mechanism [3]. The diagram of EB mechanism is shown in Fig.2. This implies that the half-life of $^{229\text{m}}\text{Th}$ is dynamically variable depending on its chemical state. The photons emitted in a direct isomeric transition from this level to the ground state should have about 350 nm wavelength, and the photons involved in the transition via EB process are deduced to correspond to visible rays. However, there has been no direct observation for the transition of $^{229\text{m}}\text{Th}$ yet. The successful observation will allow us to research the details of EB mechanism.

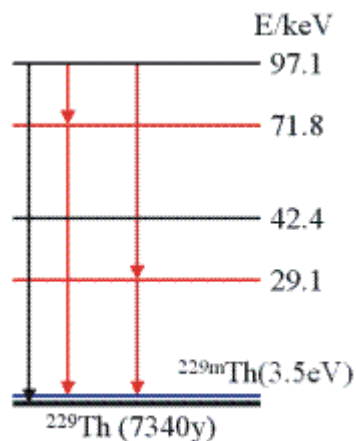


Figure 1. Level scheme of ^{229}Th .

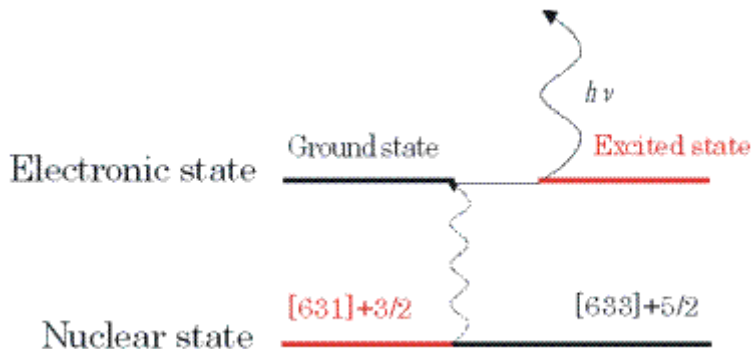


Figure 2. Diagram of Electron Bridge Mechanism.

The ^{233}U sample contains a given amount of $^{229\text{m}}\text{Th}$ produced through an α -decay from ^{233}U with a branching ratio of about 1-2 percents. Several kinds of experiments were performed by other groups for the observation of photons emitted from the ^{233}U sample [4,5]. These observations were not successful,

however, owing to the α -particle-induced fluorescence of the materials (nitrogen and quartz, etc.) around the radioactive sample [6].

We introduce a new photon detection system and an α -ray spectroscopic technique to investigate the decay property of ^{229m}Th . The ^{229m}Th samples were prepared by two different methods, chemical separation of decay product from ^{233}U or ^{229}Ac , and direct production by several nuclear reactions. Here preliminary results are reported.

Experimental

The new method of production of ^{229m}Th was performed by novel method using several nuclear reactions: $^{228}\text{Ra}(n,\gamma)^{229}\text{Ra}$, $^{232}\text{Th}(\gamma,p2n)^{229}\text{Ac}$, $^{230}\text{Th}(\gamma,n)^{229}\text{Th}$, $^{232}\text{Th}(p,p3n)^{229}\text{Th}$ and $^{230}\text{Th}(p,d)^{229}\text{Th}$. ^{229}Ra decays into ^{229}Ac ($T_{1/2} \approx 4\text{m}$), and ^{229}Ac decays into ^{229}Th ($T_{1/2} = 62.7\text{m}$). In the decay process from ^{229}Ac , ^{229m}Th is expected to be produced with high probability.

We tried to observe the decay from ^{229m}Th directly by two different methods to investigate the decay mechanism of ^{229m}Th . One is to detect the ultraviolet and visible photons from ^{229m}Th . Although this attempt has not been successful yet, it is essential to investigate the EB mechanism. Photon measurement was performed only for ^{229}Th samples separated from ^{233}U or ^{229}Ac , because the detector was very sensitive to each radiation and thermal phenomenon. The other method is to detect the α particle emitted from ^{229m}Th . We may observe the α rays from ^{229m}Th , since the partial half-life of α -decay in ^{229m}Th is considered to be shorter than that in ^{229}Th as will be mentioned below. The results obtained by the photon measurement can be attributed to the nuclear phenomenon by taking the results for the α -ray measurement into account.

1) Sample preparation

a) α -decay from ^{233}U

The half-life of ^{229m}Th has not been determined experimentally yet, estimated in wide range from about $\sim 10^{-2}\text{s}$ to tens of hours [1,7]. Therefore we developed a rapid ion exchange apparatus so as to make successfully the measurement even when the lifetime was rather short.

The experimental procedure is as follows. First ^{233}U was adsorbed on an anion exchange resin layer in 8M hydrochloric acid solution. Making use of a chemical property that the daughter nuclides of ^{233}U cannot be adsorbed to the resin layer, ^{229}Th grown up during a certain time (Growth Time) was eluted and separated from ^{233}U . It takes only a few minutes for this separation.

Not only the elution peak but all the other range of the elution were also measured to confirm whether the photon emission derived from ^{229m}Th . The ^{229g}Th sample as well as the separated ^{229}Th sample was measured under the almost same conditions to evaluate the effects of fluorescence of thorium atoms and those of radiation from ^{229}Th nuclei.

b) $^{228}\text{Ra}(n,\gamma)^{229}\text{Ra}$

^{228}Ra was prepared by separating Ra from a ^{232}Th sample in radio-equilibrium. The ^{232}Th sample (thorium nitrate $\text{Th}(\text{NO}_3)_4 \cdot 5\text{H}_2\text{O}$) was dissolved in 0.5M Nitric acid. All elements in the decay-chain of ^{232}Th except Ra were precipitated by adding ammonia solution. After centrifuging Ra solution was obtained. Th was completely removed by anion exchange method. Then the ^{228}Ra solution sample was dried up on a quartz boat.

The neutron irradiation was performed in Kyoto University Reactor. ^{228}Ra of about 220kBq was prepared as a target. Neutron flux was 2.8×10^{13} n/s. The duration of irradiation was 60 minutes. After

irradiation the sample was rapidly dissolved in 2M HCl, and Ac was separated by a cation exchange method. We measured the γ -ray energy to ascertain the production of ^{229}Ac . The separated Ac solution sample was divided in half, one was assayed for α -ray measurement. The other was left for 3 hours until ^{229}Th was grown fully. Th was isolated by the anion exchange method, and a part of that was assayed for photon measurement and the residual for α -ray measurement.

c) $^{230}\text{Th}(\gamma, n)^{229}\text{Th}$, $^{232}\text{Th}(\gamma, p2n)^{229}\text{Ac}$

About 30 μg of 95% ^{230}Th molecular-plated on a 5N aluminum plate was enclosed in a quartz tube for Bremsstrahlung irradiation. About 1.5g of ^{232}Th oxide was also enclosed in a quartz tube and used as a target. The irradiation was carried out using the Electron Linear Accelerator of Tohoku University (Linac). The linac was operated at electron energies of 27 MeV with the beam pulse width of 3 μs the peak current around 100 mA, and the pulse repetition rate of 300 s^{-1} .

After the irradiation, thorium isotopes were chemically separated from the other nuclear reaction products and fission products by the anion exchange and cation exchange method. The thorium isotopes in the effluent were then coprecipitated with samarium trifluoride by adding 30 - 250 μg samarium and hydrofluoric acid solution.

d) $^{232}\text{Th}(p, p3n)^{229}\text{Th}$, $^{230}\text{Th}(p, d)^{229}\text{Th}$

Proton irradiation was carried out with AVF Cyclotron at Research Center for Nuclear Physics in Osaka University. 770 μg of ^{232}Th molecular-plated on a 5N aluminum plate was prepared as a target. Proton beam energy was 34-36 MeV, and the beam current was about 1 μA . The duration of irradiation was 8 hours.

About 5 μg of ^{230}Th was used for irradiation. The target was exposed to about 14.8 MeV, 1 μA proton beam for 8 hours. Another target was irradiated for 1 hour in the same beam condition. Immediately after the irradiation, this sample was measured by silicon detector without chemistry to confirm the production of ^{228}Th , Pa and Ac. At this beam energy it is expected that the nuclear reaction producing compound nuclei would be inhibited by the coulomb barrier, only ^{229}Th should be produced.

Pa and fission products produced simultaneously were first removed by an anion exchange separation after the irradiation. After removal of aluminum by precipitation adding NaOH, the Th fraction was separated from Ac and other fractions by a cation exchange method. Acquired sample was coprecipitated with samarium, and assayed for an α -ray measurement.

2) Measurements

a) Photon measurement

Low noise photomultiplier (PM) was used for the photon detection. PM was installed in a PM cooler to lower the thermal noise. Further, the oval reflector was employed, as shown in Fig.3, to focus as many photons emitted from the sample as possible on the photocathode (5mm \times 8mm) of PM. The output signals from PM was transformed, through only Pre-Amplifier and Discriminator, to MCS-mode data collecting system.

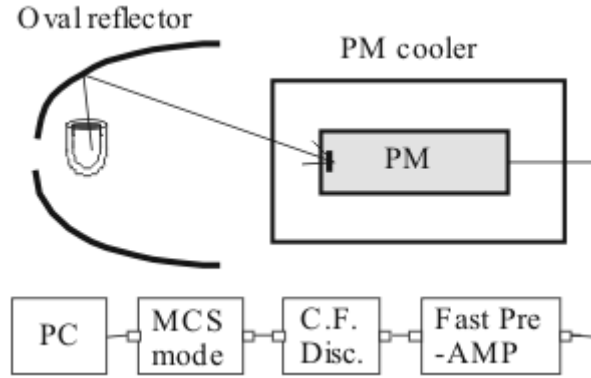


Figure 3. Photon detection system with oval reflector.

The sample measured was usually solution put in a quartz tube ($\phi 8\text{mm}$, 1cm). Several droplets of eluent at elution peak of thorium were collected in it.

b) α -ray measurement

The most favored α -transition from the ground state of ^{229}Th feeds to the $5/2+[633]$ state at 236.3 keV level of the daughter ^{225}Ra , and only rather weak α -transitions are observed in the higher energy range, as shown in the column for ^{229}Th in Table 1. The transition from ^{229}Th to the $149.96\text{ keV } 3/2+[631]$ level of ^{225}Ra ($E_{\alpha}=4.930\text{ MeV}$) that is expected to be the most favored α -transition from $^{229\text{m}}\text{Th}$ has a branching ratio of only 0.16% . In addition, the α -transition to the parity coupled $3/2+$ state at 42.77 keV that is assigned to the rotational band of the ground state of ^{225}Ra ($1/2+[631]$) is also expected to be another favored α -transition from $^{229\text{m}}\text{Th}$. As a result, the α -particles from $^{229\text{m}}\text{Th}$ have higher energies than those from ^{229}Th . This implies that the partial half-life of the α -transition of $^{229\text{m}}\text{Th}$ is considerably shorter than that of ^{229}Th , and that the α -particle might be observable when $^{229\text{m}}\text{Th}$ is produced by a suitable reaction.

Table 1. Levels of ^{225}Ra and the α -transition ratio from ^{229}Th .

Orbit	Excitation Energy/keV	α -branch		E_{α}/Mev
		^{229}Th (%)	$^{229\text{m}}\text{Th}$	
[631]1/2+	0	weak	favored	5.079
3/2+	42.77	0.24	strong	5.036
5/2+	25.41	6.6	favored	5.053
7/2+	111.60	5.97		4.968
9/2+	100.5	3.17		4.978
[631]3/2+	149.96	0.16	strong	4.93
5/2+	179.75	10.2	weak	4.901
7/2+	243.6	5.0		4.836
[633]5/2+	236.3	56.2	weak	4.845
7/2+	267.9	9.3		4.815
9/2+	321.8	1.9		4.761

The sample for α -spectrometry was prepared by coprecipitating thorium isotope with samarium as fluoride or hydroxide on 0.1 μm or 0.02 μm pore size membrane filter. The precipitate was subjected to α -spectroscopy using a 450 or 900 mm^2 silicon detector.

Results and Discussion

1) Photon measurement

Photon emissions were observed for the solution samples separated from both ^{233}U and ^{229}Ac produced by $^{228}\text{Ra}(n,\gamma)^{229}\text{Ra}$ reaction. There was no decay component in the time dependence as shown in Fig.4. The eluent sample that is lying out of elution peak position also emitted a few visible or ultraviolet photons. It is difficult to attribute the origin of photon emission to $^{229\text{m}}\text{Th}$ nucleus.

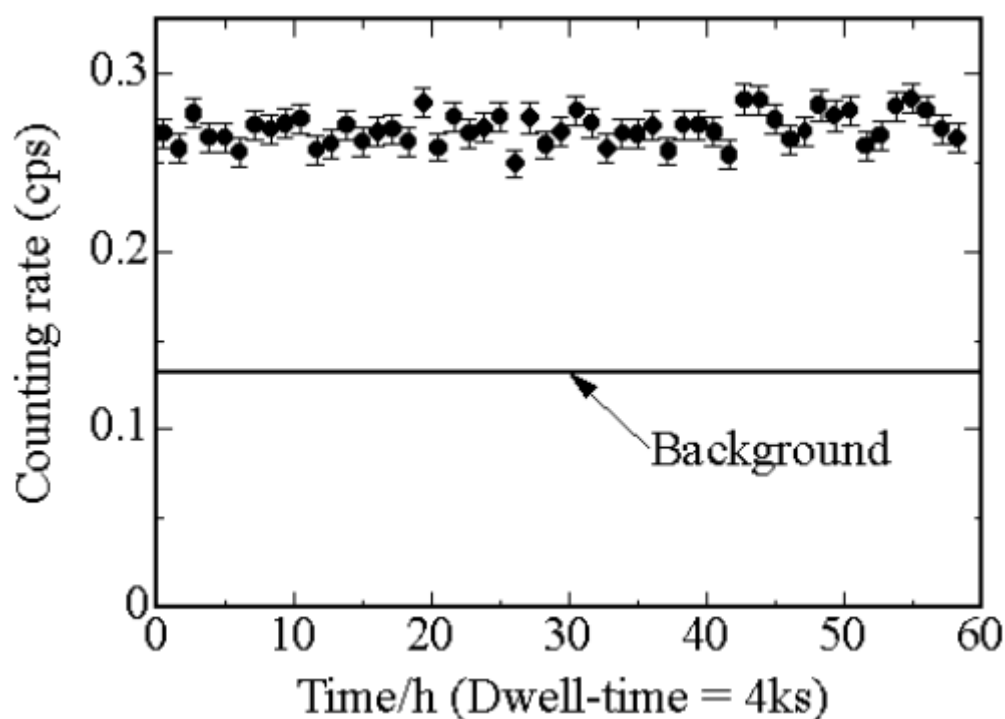


Figure 4. An example of photon measurement result from ^{229}Th solution sample chemically separated from ^{233}U .

Little photon emission was observed from $^{229\text{g}}\text{Th}$ sample. The fluorescence of thorium atoms and the other photons derived from α -particle emission of $^{229\text{g}}\text{Th}$ do not contribute to the detected photons.

The transition energy of $^{229\text{m}}\text{Th}$ may lie out of the energy region of the present detector.

Development of a spectroscope for one-photon counting is under consideration to distinguish the decaying component of a certain wavelength. We are measuring photons with the detector working in higher energy region.

2) α -ray measurement

In the $^{228}\text{Ra}(n,\gamma)^{229}\text{Ra}$ experiment, α -ray spectrum in the region of interest for $^{229\text{m}}\text{Th}$ was obscure because of the disturbance of the tail of α -ray peaks of ^{228}Th . γ -rays from ^{229}Ac (164.5 keV) were measured and the production of ^{229}Ac was ascertained.

In the $^{230}\text{Th}(\gamma, n)^{229}\text{Th}$ and $^{232}\text{Th}(\gamma, p2n)^{229}\text{Ac}$ (see Fig.5) experiments, α -ray peak of ^{229}gTh appeared to be detected in the α -ray spectrum of both experiments. There were some peaks in the energy region of $^{229\text{m}}\text{Th}$, but the contribution from ^{231}Pa disintegrated from ^{231}Th was not negligible for the experiment using ^{230}Th target. The half-life of $^{229\text{m}}\text{Th}$ would be too long as compared with the estimation, if the α -decay of $^{229\text{m}}\text{Th}$ were observed as well as ^{229}gTh .

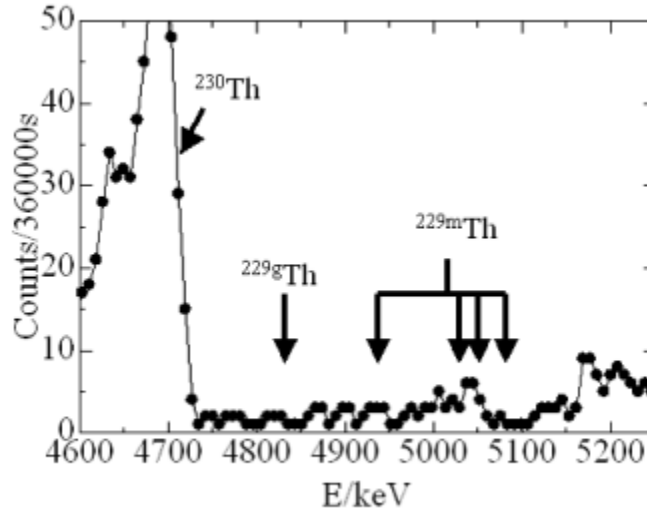


Figure 5. α -ray measurement result of ^{229}Ac sample chemically purified from $^{232}\text{Th}(\gamma, p2n)^{229}\text{Ac}$ reaction products.

In the $^{232}\text{Th}(p, p3n)^{229}\text{Th}$ (see Fig.6) and $^{230}\text{Th}(p, d)^{229}\text{Th}$ experiments, α -rays from ^{229}gTh were observed. However, these of $^{229\text{m}}\text{Th}$ were not measured clearly. This result implies that the half-life may be shorter than a few hours.

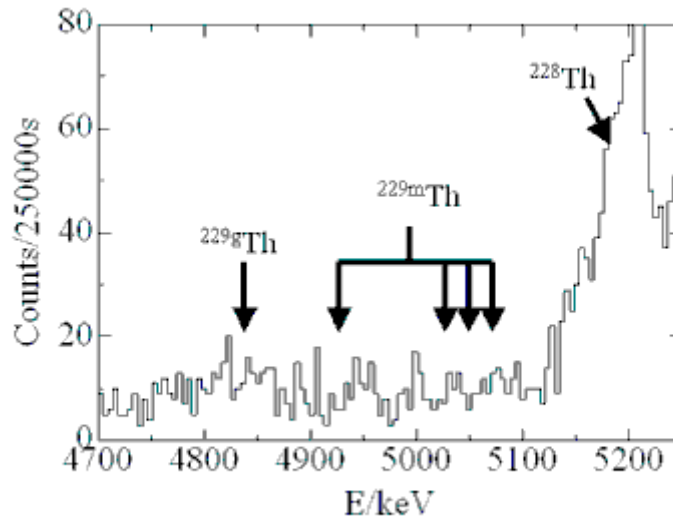


Figure 6. α -ray measurement result of ^{229}Th sample chemically separated from $^{232}\text{Th}(p, p3n)^{229}\text{Th}$ reaction products.

Consequently we could not observe the decay of $^{229\text{m}}\text{Th}$ or determine the half-life from the present results. Additional experiments and improvement of the detection methods are in progress.

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Super- and hyperdeformed isomeric states and long-lived superheavy elements

A. Marinov¹, S. Gelber¹, D. Kolb², R. Brandt³, R.V. Gentry⁴, A. Pape⁵

¹ The Hebrew University of Jerusalem, Israel

² University GH Kassel, Germany

³ Philipps University Marburg, Germany

⁴ Earth Science Associates, USA

⁵ IN2P3-CNRS/ULP Strasbourg, France

marinov@vms.huji.ac.il

In recent years long-lived super- and hyperdeformed isomeric states have been discovered [1-4]. It was found that these isomeric states live much longer than the corresponding nuclei in their ground states (see Table 3 in [4]), and in addition, they have unusual radioactive decay properties. Thus, an isomeric state in the second minimum of the potential energy surface (a superdeformed (SD) isomeric state) may decay by relatively high energy and retarded α particles to the ground state, or to the normal deformed states, of the daughter nucleus, and also by low energy and enhanced α particles to the second minimum of the potential in the daughter. In addition it may also decay by very retarded proton radioactivity. An isomeric state in the third minimum of the potential (a hyperdeformed (HD) isomeric state) may decay by relatively high energy and retarded α particles to the second minimum of the potential in the daughter nucleus, or by low energy and enhanced α particles to the third minimum of the daughter. All these new and unusual radioactive decay properties have been found experimentally [1-4].

Based on these results the discovery [5,6] of element 112, back in 1971, produced via secondary reactions in CERN W targets irradiated with 24 GeV protons (see also [7,8]), has consistently been interpreted [4]. The long lifetime of several weeks, as compared to typical lifetimes of less than 1 ms [9], shows that a long-lived isomeric state rather than the normal ground state was produced in the reaction. The deduced fusion cross section in the region of a few mb, as compared to about 1 pb obtained in ordinary heavy ion reactions [9], is due to two effects:

a) The projectile in the secondary reaction experiments is not a normal nucleus in its ground state, but rather a fragment that has been produced by the high energy proton within about 2×10^{-14} sec before interacting with another W nucleus in the target. During this short time it is at high excitation energy and quite deformed. Deformations increase the fusion cross section by several orders of magnitude as is well known from the sub-barrier fusion phenomenon [10] (see Fig. 10 in [8] and Fig. 7 in [4].)

b) The production of the compound nucleus in a super- or hyperdeformed isomeric state is much more probable than its production in the normal deformed ground state. The shapes of the compound nucleus in these isomeric states are close to those of the projectile-target combinations in their touching points. Therefore, much less inter-penetration and dissipation are needed in the formation of the compound nuclei in these isomeric states as compared to their production in the ground states (see Fig. 8 in [4]).

The discovery of the long-lived super- and hyperdeformed isomeric states enables one also to consistently interpret the unusually low energy and very enhanced α -particle groups seen in various actinide fractions separated from the same CERN W target. Thus the 5.14, 5.27 and 5.53 MeV α -particle groups, with corresponding half-lives of 3.8 ± 1.0 yr, 625 ± 84 d and 26 ± 7 d, seen in the Bk, Es and Lr-No sources, respectively, have consistently been interpreted, both from the point of view of their low energy and their five to seven orders of magnitude enhanced lifetimes, as possible $II^{\min} \rightarrow II^{\min}$, $III^{\min} \rightarrow III^{\min}$ and $III^{\min} \rightarrow III^{\min}$ transitions in ^{238}Am , ^{247}Es and ^{252}No [4].

Based on the newly observed modes of radioactive decay of the super- and hyperdeformed isomeric states, consistent interpretations have recently been suggested by us for previously unexplained phenomena seen in nature [11,12]. These are the Po halos, the low-energy enhanced 4.5 MeV α -particle group proposed to be due to an isotope of a superheavy element with $Z=108$, and the giant halos.

Po Halos were observed in mica minerals [13,14] where the concentric halos correspond to the decay chains of ^{210}Po , ^{214}Po and ^{218}Po . Since the lifetimes of these isotopes are short, and halos belonging to their long-lived precursors from the ^{238}U decay chain are absent, their origin is puzzling. It has been suggested [11,12] that their origin might be due to the existence of long-lived super- and hyperdeformed isomeric states in nuclei around ^{210}Po , ^{214}Po and ^{218}Po which undergo β - and γ -decays to the ground states of these isotopes.¹

The second unexplained phenomenon is the observation [16-19], in several minerals, of a low energy 4.5 MeV α -particle group with an estimated half-life of $(2.5 \pm 0.5) \times 10^8$ yr which, based on chemical behavior, has been suggested to be due to the decay of an isotope of Eka-Os ($Z=108$; Hs). However, 4.5 MeV is a low energy compared to the predicted 9.5 - 6.7 MeV for β -stable isotopes of Hs [20-22], and $T_{1/2} = 2.5 \times 10^8$ yr is too short by a factor of 10^8 , compared to predictions [23,24] from the lifetime versus energy relationship for normal 4.5 MeV α particles from Hs. It was recently shown [11,12], though, that these data can be quantitatively understood as a hyperdeformed to hyperdeformed transition from an isotope with $Z=108$ and $A \approx 270$. The low energy agrees with extrapolations from predictions [25] for $\text{III}^{\text{min}} \rightarrow \text{III}^{\text{min}}$ α transitions in the actinide region, and a half-life in the region of 10^9 yr is obtained if one takes into account in the penetrability calculations typical deformation parameters for a hyperdeformed nucleus.

Still another unexplained phenomenon is that of the giant halos [26]. Halos, with radii that fit the known ranges of 10 and 13 MeV α particles, have been seen in mica [26]. Unlike the situation with the Po halos, here it is not absolutely certain that their origin is from such high energy α particles [26-28]. However, if they are, then their existence is puzzling. For nuclei around the β -stability valley, 10 and 13 MeV α particles are respectively predicted [20-22] for Z values around 114 and 126. The estimated [23,24] half-life for 10 MeV α 's in $Z=114$ nuclei is about 1 sec, and for 13 MeV α 's in $Z=126$ nuclei, it is about 10^{-4} sec. It is not clear how halos with such high-energy α particles and such short predicted lifetimes can exist in nature.

Here too an interpretation in terms of hyperdeformed isomeric states has been given [12]. A good candidate for the sequence of events producing the 10 MeV halo is a long-lived HD isomeric state decaying by a 4.8 MeV $\text{III}^{\text{min}} \rightarrow \text{III}^{\text{min}}$ α transition, followed by $\beta^+(\text{EC})$ transitions to a normal state which decays by 10 MeV α particles. As a specific example, one may consider the following scenario where a HD isomeric state in $^{282}114$ decays by 4.8 MeV α 's to a HD isomeric state in $^{278}112$, followed by two $\beta^+(\text{EC})$ decays to a normal deformed state or to the g.s. of $^{278}110$. This latter nucleus is predicted [20-22] to decay by 10 MeV α particles. For deformation parameters which are typical for a HD nucleus, the predicted $T_{1/2}$ value for a 4.8 MeV $\text{III}^{\text{min}} \rightarrow \text{III}^{\text{min}}$ α transition from $^{282}114$ is $10^8 - 10^{11}$ yr [12], and the sum of the two Q_β values of above 6 MeV [20-22] makes the transition from the isomeric state in the third minimum to a normal state in one of the daughter nuclei possible.

Similarly, for the 13 MeV halo a possible scenario has been suggested [12] where a HD isomeric state in $^{316}126$ decays by a $\text{III}^{\text{min}} \rightarrow \text{III}^{\text{min}}$ low-energy α transition of about 5.1 MeV to $^{312}124$, followed by two $\beta^+(\text{EC})$ transitions, leading to the g.s. of $^{312}122$. The $^{312}122$ nucleus is predicted [20,21] to decay by α particles of around 13 MeV. For a 5.1 MeV HD to HD α transition from $^{316}126$, the predicted [12] half-life, using the parameters of Ref. [29] for a HD shape of ^{232}Th , is 3×10^{11} yr. (Larger deformation parameters give shorter lifetimes).

The above analysis suggests that primordial heavy and superheavy nuclei in long-lived isomeric states might exist in nature. A program has been started to search for such nuclei in petzite (Ag_3AuTe_2) and monazite ($(\text{Ce},\text{La},\text{Th})\text{PO}_4$) minerals using the accelerator mass spectrometry (AMS) system [30,31] of the Weizmann Koffler Pelletron accelerator in Rehovot. The first mineral was chosen since there is an

indication that induced Po X-rays in such a mineral from Romania has been observed [32]. The second mineral is the same as the one where the giant halos were found [26]. A progress report will be given.

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